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DISCUSSION OF PROGRESS REPORT ON STUDIES ON THE DESIGN OF STABLE CHANNELS BY THE BUREAU OF RECLAMATION PROCEEDINGS-SEPARATE NO. 280

SERGE LELIAVSKY,[1] M. ASCE—Professor Lane has produced a very complete summary of work on the problem of Scour in Canals to which only minor additions are possible. For instance, the fact that in Professor White's tests on scour, the angle of repose was used in a more general sense than in the paper under review, may possibly widen the general outlook on the problems dealt with therein. In fact, whilst Professor Lane introduces the angle-of-repose concept starting with the side-slopes, Professor White begins with the horizontal bed-surface[2] and demonstrates experimentally that the scour criterion for such a plane is capable of being expressed in terms of this same angle.

On the other hand, it may also be interesting to recall, that a paving, consisting of a coarser grained material than the average which Professor Lane found to have naturally formed on the bed surface on the San Luis Valley canals, has been obtained, earlier, experimentally, in Professor Rouse's well known tests.[3] The result is perhaps important as a point in the argument in favour of the effective size of the grain being larger than the median. It is, consequently, desirable to continue these experiments, in order to ascertain the reason of the sudden change in conditions, when the size of the grain is reduced to less than 5mm.

The writer wishes to emphasize that these are very minor remarks only, as compared with the splendid piece of research work presented in Professor Lane's paper. What makes it even more valuable is the fact that it constitutes the first genuine attempt to rationalize a design problem, which heretofore has been solved by empirical (or semi-theoretical) equations; and therefore, even if some among Professor Lane's solutions are not final, his paper opens, nevertheless, the door for further widespread developments of the rational canal-design method.

It is this particular aspect of Professor Lane's paper which calls for especial attention, since, in the writer's opinion, the paragraph entitled "Further Studies", is the only part of the paper upon which opinions might possibly differ, for the program sketched out therein lays possibly too much stress on the conventional approach to the tractive-force problem and canal designers may perhaps disagree with the principle of

1. Civ. and Hydr. Engr., Cairo, Egypt.
2. C. M. White, "The Equilibrium of Grains on the Bed of a Stream," Proc. Royal Soc., Series A, Vol. 174, Experiments 7 and 9, Table 2, page 331.
3. H. Rouse, "Criteria for Similarity in the Transportation of Materials," Proc. Hydr. Conf., Univ. of Iowa, Bull. 20, 1940.

canalising the bulk of the relevant research into one single channel.

In this connection it will be realized that the use of the tractive force in Professor Lane's method is determined by the following fundamental points: (a) the distribution and local intensities of the tractive forces are calculated from either isovels, velocity equations or membrane analogies which, presumably, are, or are meant to represent, average in time values, (b) the tractive forces are assumed parallel to the axis, (c) the "lift", i.e. the kinetic force normal to the surface of the channel is disregarded, and (d) the loci of permanent local accelerations are ignored. In any case if the foregoing interpretation of Professor Lane's method is wrong, or not accurate, many readers will, certainly, be grateful for additional explanations on the subject.

In so far as they reflect on the program of future studies, these four postulates will next be considered seriatim.

In regard to (a) Professor Lane has shown in an earlier publication[4] that the capacity of the water to dislodge sediment grains does not depend on the average flow conditions, nor on the maximum values of the relevant parameters, but on the whole range of the turbulent pulsations, as determined by the Gaussian frequency curve; which is to be compounded in such computations, with the frequency curve of the grain sizes.

Since there is no reference to this point in Professor Lane's new paper, it is not quite clear whether the curves in his diagrams refer to averages or to maximum values of the fluctuating tractive force at a point; or as to that, to some "effective" parametrical value thereof, which is chosen, within the fluctuating range, in such a manner as to assess correctly its true quantitative scour action.

Had the fluctuations of the local tractive forces at the individual points of the perimeter, been insignificant, or had they been rigidly correlated with the respective averages, the point of this argument would not have mattered very much, for the average might have, then, been chosen as the significant parameter; this, however, does not seem to be the case. For instance Professor White concludes that in certain cases the maximum tractive force is 2.25 times the average, whilst in others it is 4.00 times the average.[5] Should the range of variation be indeed as high as that, the quantitative concept of a local tractive force would appear illusory, unless its relation to that range were fully and explicitly defined. The point needs obviously to be investigated more fully.

It is, therefore, tentatively suggested to include in the program of future studies the problem of the pulsations of the drag force, in so far as these pulsations affect the stability of the grains forming the channel. The method of this study is, of course, left to the officers in charge of the investigation, but the use of the ultra-microscope, as in Fage's experiments,[6] is mentioned, for information.

Turning, next, to point (b), it will be remembered that in spite of all precautions taken by Professor Vanoni to produce parallel flow in a

4. E. W. Lane and A. A. Kalinske, "The Relation of Suspended to Bed Material in Rivers", Trans. Amer. Geoph. Un., 1939, p. 637.
5. Loc. cit., pp. 328 and 333.
6. Fage, Rep. Aero. Res. Comm., London, 1933.

straight flume, sediment transportation in his experiments[7] nevertheless, took place in the form of bands, which were symptomatic of the existence and the sediment-carrying capacity of well-defined, permanent and regularly arranged cross-currents. This case is one instance only, among a large variety of facts showing that the problem in hand is basically three-dimensional, viz., that, depending on the specific circumstances of the case, diagonal tractive force might (or might not) be more important than parallel forces. Hence, the number and shape of secondary circuits for any given type section is another item of research, which may, perhaps, be proposed for the program of future studies; inclusive of the theoretical approach, as initiated by Prandtl[8] and of the experimental methods such for instance as applied by Lossievsky.[9] In fact, in studying this problem we should not ignore the fact that Professor White observed[10] that the granular bed in a diverging flume was extremely active, in spite of a negligible mean drag. Disregarding the non-parallelism of the flow does not seem, therefore, the attitude to be adopted in working out the program for the new proposed studies concerning the effect of the drag on the granular channel materials.

It is, however, the point (c) which deserves particular attention in connection with these studies, for no conclusive proof has thus far been produced that "lift" was to be disregarded, and scour analysis based exclusively on tangential forces.

In fact, "lift", or the kinetic hydraulic force normal to the surface of the channel, appears, as the center of interest, in a number of papers on sediment movement and allied problems, and, although some among the modern writers on the subject[11] quote Professor White as having demonstrated that lift is non-existent, or, possibly, negligible, the method of this demonstration is subject to considerable doubt. For, had there been no vertical component transmitted by the string to the experimental wax grain which was attached to it and placed, in this experiment, on the bottom of the experimental flume, this grain must have risen to the surface of the flowing water, due to the action of the buoyancy alone, quite apart from the effect of lift.

What actually occurred was than any tendency of this grain to rise was prevented by the impact of the water on the string—a well-known design fallacy, common to the numerous "tachometers", which, in the seventeenth century, were used (or misused) in Italy, and impeded to so great an extent the advance of the hydraulic science of the period.[12]

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7. V. A. Vanoni, "Transportation of Suspended Sediment by Water", Trans. ASCE., Vol. 111, p.67.
8. L. Prandtl, "Uber die ausgebildete Turbulenz", Proc. 2nd. Int. Congr. for Appl. Mech., Zurich, 1927, p.62.
9. Cf. M. Welikanov, "Flussbettbewegungen und Geschiebefuhrung", 5th Hydr. Confer. of Baltic States, Helsinki, 1936.
10. Ibid. p. 333.
11. Cf. Kalinske, "Movement of Sediment as Bed Load in Rivers", Trans. Am. Geoph. Un., Vol. 28, No. 4, p. 616.
12. Serge Leliavsky Bey, "Historic Development of the Theory of the Flow of Water in Canals and Rivers", The Engineer, London, April 13, 1951, p.467.

The fact, therefore, that Professor White's grain did not rise to the surface of the flowing water, cannot be taken to provide evidence that lift is negligible; particularly since, according to his own statement,[13] Fage's unpublished experiments show that "lift" is at least as large as drag.

Various mechanical "models" have been suggested in order to explain the action of the lift; for instance, according to Einstein[14] and Rubey[15] lift is a matter of pulsations, whilst Jeffreys[16] conceives it as a component of temporal average forces. The trouble about all these "models" is that whilst obvious to the scientist, they do not appear convincing to a practising designer. A force parallel to the direction of the flow is evident, but, unless its nature is clearly demonstrated, a force normal to the flow, is an abstraction.

From this standpoint an elementary but obvious "model" explaining the kinetic "lift" is desirable.

Taking, therefore, as datum the horizontal (or nearly horizontal) plane AB (see Fig. 1 on the annexed Plate 1), representing the average surface of a granular channel bed, the relative position of an individual grain belonging to, or forming part of, this surface, may be defined as follows: highest, when the particle is above the plane (as in a), and lowest, when it is entirely below the plane (as in b). In the average position of the particle, the plane must, therefore, strike its center (as in c).

This average position can, consequently, be taken as a starting point for a preliminary "statistical" examination of the problem. The advantage of this approach is that we can, thus, draw a parallel between the phenomena of scour and sphere-drag, and obtain a general idea about the former, from the abundant information available about the latter; for instance, in Fig. 2 (see same Plate), which is based on this analogy, we discriminate between three possible flow patterns near and around a sediment grain, which show: (a) that the drag and the lift, cannot be represented by one and the same parameter applicable to all the phases of flow and to all the shapes and arrangements of grain; (b) that changes from one flow pattern to another are likely to occur suddenly (as they sometimes do in experiments with sphere-drag), which furnishes a plausible explanation of the too often disregarded fact that the intensity of the scouring action does not always develop gradually, as must have been the case had the traditional drag formulae been rationally correct. But, as observed in numerous experiments, scouring action undergoes abrupt and apparently anomalous alterations, which however can only be due to sudden changes in the flow patterns for the bulk (in the statistical sense of the term) of the grains, (c) that the vertical component of the kinetic force applied to the particle is directed upwards, corresponding to the vacuum pressures observed in the sphere-drag experiments.

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13. Loc. cit. p. 333.
14. H. A. Einstein, "Formulas for the Transportation of Bed Load", Proc. ASCE, March 1941, p.351.
15. W. W. Rubey, "The Force Required to Move Particles on a Stream Bed", Prof. Mem., U. S. Geol. Survey, No. 189-E, 1938.
16. H. Jeffrey, Proc. Camb. Phil. Soc., 1929, 25, 272.

This vertical component we describe as "lift".

Better to understand the argument of this last point, attention is directed to Fig. 3 in the same Plate, which represents an experiment published by the writer as early as 1914.[17] The model of an air-ship hanger was tested in a wind tunnel, in order to find the wind forces for its structural design. The point of the experiment was, that, in spite of the wind direction being inclined to the horizontal (10^{o} subtangent angle, as shown in the diagram), the resultant wind force applied to the building was directed upwards, and not downwards, as the standard specifications would have it.

This result is in full agreement with the well known fact that, during severe storms and hurricanes, roofs of buildings are never pressed downwards, but are frequently lifted from their original positions and transported to surprisingly long distances therefrom.

Should another obvious and elementary application of the same principle be deemed necessary, or desirable, as another illustration of the lift model, we may cite the common vaporizer, shown in Fig. 4. It consists of a combination of two tubes, one being vertical and the other horizontal, which are held together, by some means or other, close to the point where their axes meet. By blowing through the upper pipe, a horizontal air current is created, which suffices to cause the liquid to rise vertically to the top of the lower pipe, and be, then, diffused in the form of a cloud. Here we have, therefore, another example of a horizontal flow, causing a vertical movement of a heavier substance.

These simple examples are believed to supply an irrefutable proof of the very real existence of the lift force; and moreover, since the horizontal component of the wind pressure acting on the shed in Fig. 3 is obviously a function of the height of the vertical wall, whilst the upward component of the force applied to the roof depends evidently on the shape of the latter, it is clear that these two forces cannot be represented by one and the same parameter. It follows that the lift problem must be envisaged as a self-contained item of research, correlated but not identified with the drag problem.

In view of the foregoing consideration it may possibly be recommended to consider the lift problem as a desirable item of the program for future research, in addition to, and parallel with, the drag problem.

With reference to the last point (see point d in page 2) attention is called to the fact that sediment transportation is a composite process consisting as it does of three distinct phases. These phases are: (I) The initial period when the particle is picked up and moves generally at a lesser velocity than the water; (II) the transportation period proper, when both velocities are of the same order of magnitude, and (III) the last stage during which the particle is dropped.

That the tractive force suffices to explain, and define, sediment behaviour in the first period, is a debatable but possibly acceptable proposition. But that it should also be taken as a significant parameter for the second phase, is more difficult to agree with. Since (with the possible exception of du-Boys' concept of a solid mass of granular bed

17. Magazine of the Institute of Engineers of Ways of Communication of Emperor Alexander I, St. Petersburg, 1914 (in Russian).

Plate 1.

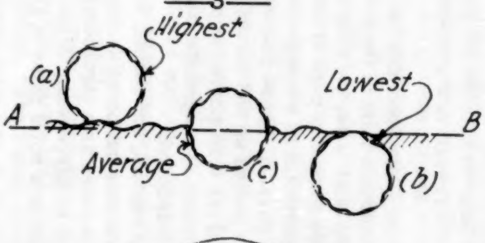

Fig. 1

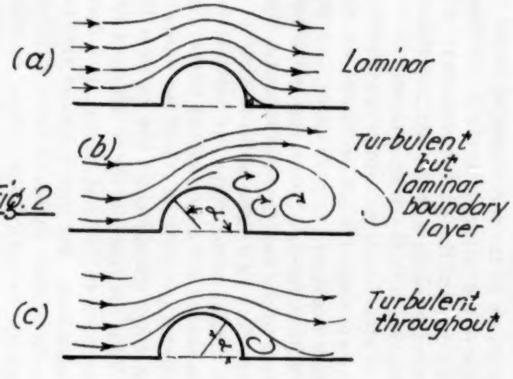

Fig. 2

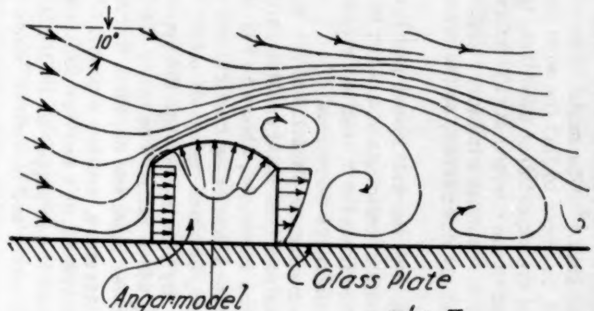

Fig. 3

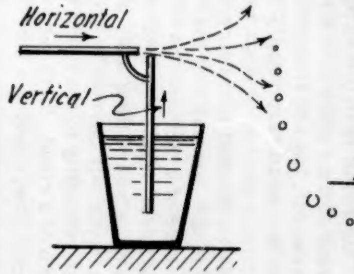

Fig. 4

material shifting bodily downstream below the physical bed of the channel) the first phase cannot be conceived without at least some reference to the second, it seems that the specific factors conditioning this second stage are also worthy of attention.

Hence, in addition to the erosive (in the narrow sense of the term) power of the stream, its "capacity to carry sediment of a certain size range" is, possibly, still another indispensable section of a consistent program of silt-stable-canal research.

In the writer's opinion, (thus-far unpublished), apart from the canal section as a whole, further research should concentrate on the local sediment carrying capacities of individual points of this section, in correlation with its typical pattern of secondary circulation; for the concept of uniform flow as presented in the elementary textbook, has outlived its time; and even if we deal with temporal averages of a generally pulsating current, secondary circulation must of necessity cause local foci of permanent accelerations and decelerations, even though the average velocity, taken for the whole section, were constant over the length of the investigated reach of the canal.

From considerations bearing on the continuity equation, it will then be found that acceleration capable of a greater sediment carrying capacity must be correlated with convergent currents, whilst deceleration, and therefore sediment deposits, must coincide with divergent currents. Hence, stable canal form is very probably a function of the cross-current pattern, and since Lossievsky[18] found that this pattern changes with the bed-to-width ratio, we have at least a glimpse of an idea as to the mechanical processes which lie behind the tendency of a stream to excavate a channel of a certain, given geometrical form.

This explanation, preliminary as it may be, may nevertheless be considered as an alternative to the concept of "incipient motion" profile, described in the paper under review, and deserves to be investigated in parallel with it.

A. NIZERY[19] and G. BRAUDEAU[20]—Professor Lane's study makes a clear distinction between the two basic problems: (1) What is the necessary hydrodynamic effort to put in motion a grain of a given material? (2) What form of section must be chosen in order that the forces applied on the material be distributed as uniformly as possible?

I - The first problem may be studied in a very wide canal with horizontal bottom. Thus the gravity will have no tangential component and the tractive force τ, the value of which is well known in this case, will be the only one acting on the grain, parallel to the wall. The grain equilibrium will be realized if the resultant of the tangential force and of the gravity is situated inside the friction cone defined by a certain angle φ. The tangential force is proportional to τ and to the grain surface, and consequently to d^2. The weight is proportional to d^3 and γ_s (density of the material under water). The equilibrium condition is therefore:

18. Loc. cit.
19. Directeur Adjoint des Etudes et Recherches d'ELECTRICITE DE FRANCE.
20. Ingénieur au LABORATOIRE NATIONAL D'HYDRAULIQUE - Chatou - FRANCE.

$$\frac{A\,\tau\,d^2}{B\,d^3\,\gamma_s} \leq tg\,\varphi$$

or

$$t \leq K\,.\,d\,.\,\gamma_s\ \ tg\,\varphi\,.$$

When the grain sizes are not too different, one can consider for all the grains only one angle φ , equal to the natural bank angle of the materials (under water). The law found in this case is again similar in form to that deduced from the MEYER PETER formula, which is currently used in Europe to study the problems relating to bed load transportation. It shows that the critical tractive force τ_c is proportional to the diameter and relative density of the grains.

We often have had the opportunity of applying this semi-empirical law, which results from a very large amount of experimental work. We always found a very good agreement with experimental results, when the conditions of application for which this law had been established were suitably satisfied. When however the grain sizes are too different, or if cohesion comes into play, there is no more agreement and it then becomes necessary to resort in each case to direct measurement of τ_c.

II - As shown by Professor Lane, the best form of section will be that for which the tractive force at each point is equal to the critical force for the materials with which the walls are built up. It is such a section which will allow the greatest mean speed for a given rate of flow, and will be therefore the most economical as regards the excavation work.

If the tractive force distribution were known for a determined form of section, it would be possible to express that the force equilibrium is satisfied at each point, in a form similar to that indicated above. It would then be possible to derive the equation of the section which complies with this condition, and also in a general manner with the five conditions indicated by Professor Lane.

But the tractive force distribution depends on the form of section and it follows that the equation found would be theoretically an integral equation.

One is therefore compelled to make hypotheses and to check if these are confirmed experimentally.

These questions are now being analysed at the Laboratoire National D'Hydraulique, at Chatou, on a canal with a length of 45 m and a width of 3,50 m. The form and size of the section, as well as the longitudinal slope of this canal can be easily varied. As we are only considering up to now the forms of section, we use as a material an uniform sand, the grains of which have very nearly 3 mm of diameter.

For a given section form and size, we increase the slope, while modifying the rate of flow at the same time, so as to obtain the uniform regime, till a bed load transportation clearly begins to occur at any point of the section.

For each regime, velocity measurements are effected at many

points. We have thus been able to obtain detailed velocity distributions for different types of sections, especially for trapezoidal ones.

From these velocity distributions the tractive force at each point has been calculated as indicated by J. B. Leighly and Professor Lane.

We have found that the experimental results did not agree with those obtained in the above manner: the bed load transportation did not begin where the calculation indicated a maximum tangential force. Perhaps this phenomenon is not alien to the existence of secondary flows above the section corners, as shown by the strong instability of the velocity measured in these zones.

On the other hand, we have calculated a section in which the tangential forces would be uniformly distributed, on the hypothesis that the tractive force at any point would be simply:

$$\gamma Z S \qquad (1)$$

with Z = depth of the considered point below the surface, and
S = slope of the water line.

It is easy to find for such a section parametrical equations of the form:

$$x = a \cos\beta$$

$$Z = \frac{a}{\sin\varphi} \int_0^\beta \sqrt{1 - \sin^2\varphi \sin^2\beta}\, d\beta \qquad (2)$$

with :

$$a = \frac{P \operatorname{tg}\varphi}{k \gamma g S} \qquad (3)$$

Here P = weight of a grain
K = coefficient of proportionality of the force applied by the water on a grain to the tractive force at the same point.
a = maximum depth. This is correlated with the slope s by equation (3).

It is further necessary to add a friction equation correlating a and S with the rate of flow.[21]

We have made experiments with such a section, in the same manner as for those considered above, and found that the bed load transportation begins almost simultaneously at all points. This would indicate therefore that the force distribution is fairly well represented by eq. (1), at least in a section, the height/width ratio of which is below a certain value, which, as a matter of fact, we have not determined.

III - It seems that one can expect from such studies more than the mere development of a rational method of calculation for canals with alluvial bottom.

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21. Another hypothesis, made by KOECHLIN about the manner in which the water acts on the grains, leads to a section, the equation of which has the form $Z = a \,.\, \sin(\operatorname{tg}\varphi \frac{x}{a})$. It is found that the sections calculated by both methods for the same regime are rather similar, though of different analytical expressions.

The application to natural watercourses of the results so obtained may be fruitful. If we consider a river meandering in a high-water bed built up by its own alluvia, observation suggests that the hydrological regimen assign to the low-water bed a certain slope. We have thus four variables, which do not appear to be independent, since the rate of flow values, for example, must determine the values of the three others. The mere knowledge of the friction law and of a specific bed load transportation law[22] does not enable one to account for this occurence. The width must appear in the lacking relation, and it seems that this cannot be other than that which expresses a certain (uniform, or non-uniform since curvature effects arise) distribution of the tractive forces, necessary for the transverse profile equilibrium.

The problem is of the same nature, although naturally more complex, owing to the fact that on one hand the rates of flow vary, and that on the other hand we consider an equilibrium with bed load transportation.

We believe that considerations similar to those used to study the equilibrium without bed load transportation under permanent regime may help to solve this important problem.

JOSÉ S. GANDOLFO[23]—The author's contribution describes new and improved methods in the design of unlined canals by means of the tractive force concept.

It gives the results of the intensive experimental works conducted at the Bureau of Reclamation under the author's supervision.

It also mentions observations, investigations and technical experiences of other countries, especially India.

The author's methods for designing stable canals in coarse and fine noncohesive material represent a practical and valuable advance in hydraulic projects.

There are many aspects of these problems which need further studies and investigations. Among them, the writer considers important to comment some ideas presented under the author's heading: "Canals Carrying Heavy Sediment Loads". The following discussion is concerned primarily with this part of the author's paper.

These canals are often in connection with natural streams and unsteady flow will be expected. If unlined, the bed is of the same nature as the heavy load material transported.

In this special case we cannot speak of stable channels because each flow has a definite mean rate of bed load transport and slope. So, in periods of lower flow, ordinary flood deposition and decreasing of general slope will be expected. In periods of great flood there are erosion and increasing of slope and rugosity. Normal flow can not remove all sizes of coarse bed load and only transports the small particles not protected in spaces between coarser particles.

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22. We call "specific bed load transportation law" the law relating the solid flow per meter of width to the hydraulic conditions relative to an infinite width.
23. Head of Hydraulic Department and Professor of the Universidad Nacional de Eva Perón (Ex-La Plata) (Argentina).

Since the canal configuration is changing continuously, it is necessary to choose a representative flow for correct design.

Hydraulic needs will be satisfied by maximum flood flow canal capacity, but alluvial requirements are connected with the necessity of establishing the prevailing flow of coarse transported material.

The product of the flow frequency and the respective canal coarse sediment transported give the frequency curve of the coarse sediment transported; this shows a maximum $\sum G'$ for a determined flow Q'.

The narrow band of flow above and below Q' carry the greatest amount of heavy material load. Then, the canal slope and alluvial bed configuration will agree well with this value of Q' (in Fig. A, Q' = 650 m^3/s). F. Schaffernak,[24] named it "bed generative flow".

In the dike improvement design of the San Juan River (Argentine) the writer found that the mean annual heavy material transport was:

G'_m = 103 kg/s; corresponds to a flow:
Q'_m = 538 m^3/s, but the mean annual flow is:
Qm = 521 m^3/s

The bed generative flow concept gave the generative coarse sediment transport as G' = 175 kg/s, and the corresponding flow as

Q' = 650 m^3/s [25]

The flood flows between 450 and 850 m^3/s transports 75% of the mean annual load; also, G' = 1,7 G'_m.

The Rhine River at Brugg Bridge, above Constance Lake[26] showed a mean annual transport during 1936 of

G'_m = 7,3 kg/s corresponding to a flow of
Q'_m = 503 m^3/s ;

but the mean annual flow during 1936 was

Q_m = 457 m^3/s

The bed generative flow concept gave the generative coarse sediment load as G' = 16,1 kg/s and the corresponding flow as Q' = 659 m^3/s.

The flood flows between 520 and 940 m^3/s transported 62% of the 1936 coarse sediment load; also G' was equal to 2,2 G'_m.

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24. F. Schaffernak: Die Theorie des Geschiebebetriebes und ihre Anwendung. Zeitschrift des österreichischen Ingenieur and Architeken-Vereines, Wien 1916, Nr.68- Neue Grundlagen für die Berechnung der Geschiebe führung in Flussläufen. Verlag:Franz Deutike.Leipzig. Wien-1922-
25. José S. Gandolfo-Estimación de la evolución del alveo de los ríos. Publicación de la Fac.de Ciencias Físicomatemáticas, Serie Segunda, 3, Nº 128, pag 245 y siguientes, Separata pag. 33 y siguientes, Universidad Nacional de La Plata (actualmente Eva Perón)-Argentina, 1940.
26. F. Nesper-Die Internationale Rheinregulierung von der Illmündung bis zum Bodensee-Schweizerische Bauzeitung, Zurich 1937- Band 110, Nr.13.

The design for International Rhine regularization from Illmündung to Bodensee was computed with G'_m; in the writer's opinion it is an insufficient dynamic design basis for rivers.[27]

If the flood-flow frequency would be constant the mean annual load basis will be correct; on the contrary, heavy material bed transport increases as flood flows decrease in frequency; the values above are illustrative.

The differences between G'_m and G' will be greater with the higher irregularity of the number and distribution of flood periods; also with the more variable intensities and duration of the flood waves.

Then, these differences will be greater in the improvement works of torrential rivers.

The mean annual bed load, if the other conditions are the same, shows a longitudinal profile of less slope and a characteristic cross section not deep enough.

Otherwise, in the mean annual coarse sediment bed load is included all the transported material, corresponding to lower and greater flood flow. For that reason, this value is highly variable.

The generative bed load flow is a value little influenced by flood flows weak in solid transported material, even if the frequency is increased.

This value is practically not modified by the extraordinary floods of low frequency, though they transport a great lot of solid bed material.

The generative bed-load flow is confined within the narrow flood-flow zone, which because of its frequency and capacity for transporting solid bed material moves the greater volume of coarse sediment.

Generative bed load flow is much less variable than mean annual flow.

In other consecutive canal stretches generative bed load flow can change through modification of the granulometric curve of the bed material or slope. This is also true for a varying flow when a tributary canal reaches the beginning of the following stretch or where there is a diversion structure.

Problems of designing canals with transport conditions that vary in consecutive stretches can be attempted as follows:

Let: generative bed load flow = Q', coarse material bed transport = G', mean diameter = d, specific gravity = ρ, dimensions of the geometrical and hydraulic canals be B (width), φ (h) (height), and i (slope); and let k = rugosity.

Use subscript 1 in the first stretch of the canal and the heavy bed material transport function:

$$G'_1 = F_1 \left[Q'_1 , i_1 , \varphi (h_1), k_1 , d_1, \rho_1 \right]$$

If G'_1 is known and if i_1 is the actual slope or another slope convenient for design, then solve the function by steps varying $\varphi (h_1)$. Immediately compute: $B_1 = \emptyset_1 \left[Q'_1, i_1 , \varphi (h_1) , k_1 \right]$.

From the variation of both i_1 and φ (h_1) in the G'_1 equation, the best B_1 value can be chosen.

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27. E. Meyer-Peter, H. Favre u R. Müller.Beitrag zur Berechnung der Geschiebefürung und der Normalprofilbreite von Gebirgsflüssen, Schweizerische Bauzeitung, Zurich, 1935, Band 105,Nr.10-

In the second stretch of the canal, with subscript 2, the continuity law of transport of heavy material for the width of the canal is:

$$G'_2 = G'_1 \left(\frac{d_2}{d_1}\right)^3 \pm G_2$$

in which $\left(\frac{d_2}{d_1}\right)^3$ represents the part of heavy transported bed material and the rest being crumbled and incorporated as suspension flow; when alluvial material is added at the beginning of this stretch G_2 has a positive value; but when there is a diversion structure or there is extraction of the coarse material, or the generative bed flow diminishes, G_2 has a negative value.

We must investigate, in all these cases, the value of Q'_2, but, if $G_2 = 0$, it is accurate enough to estimate $Q'_2 = \sim Q'_1$.

If there is a discontinuity in the heavy solid material transported in any stretch of the canal ($G_r \neq 0$), the corresponding G'_r and d_r values, will be the basis for solving G' in the consecutive stretches of the canal.

In the second canal stretch, the slope i_2 can be solved:

$$f_2\ (i_2) = \frac{G'_2}{Q'_2} \quad f_2 \left[\varphi(h_2),\ k_2\ ,\ d_2\quad \rho_2\right].$$

The second member is known by giving values to $\varphi\,(h_2)$.
However:

$$f_2\ (i) = f_2 \left[\varphi\,(h_2),\ k_2\ ,\ d_2\ ,\ \rho_2\ ,\ i\right] \quad ;$$

by giving values to i, $f_2(i)$ can be solved and the curve for $\left[i, f_2\ (i)\right]$ drawn.

In this diagram the ordinate $f_2\ (i_2)$ gives the slope i_2.

Finally: $B_2 = \varnothing_2 \left[Q'_2,\ i_2\ ,\ \varphi\,(h_2)\ ,\ k_2\right]$

The best B_2 value can be chosen from the variation of $\varphi\,(h_2)$; solve again for $f_2\ (i)$ and drawn the new diagram $\left[i,\ f_2\ (i)\right]$.
Immediately other values of i_2 and B_2 can be computed.

After the dimensions of the cross section of the canal for heavy material transport have been computed the hydraulic capacity for maximum project flow must be computed.

The writer, in the contribution[25] gives examples of several characteristic cross section applying Meyer-Peter, Favre, Müller's formula for heavy solid transport. The procedure is general, and can be applied with any other heavy solid transport formula for computing G'. The Einstein formula[28] is the most advanced, but of laborious application.

In the writer's project of an improved dike for the San Juan River,

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28. H. A. Einstein—The bed load function for sediment transportation in open channel flows, U.S. Department of Agriculture, Technical Bulletin No. 1026, 1950.

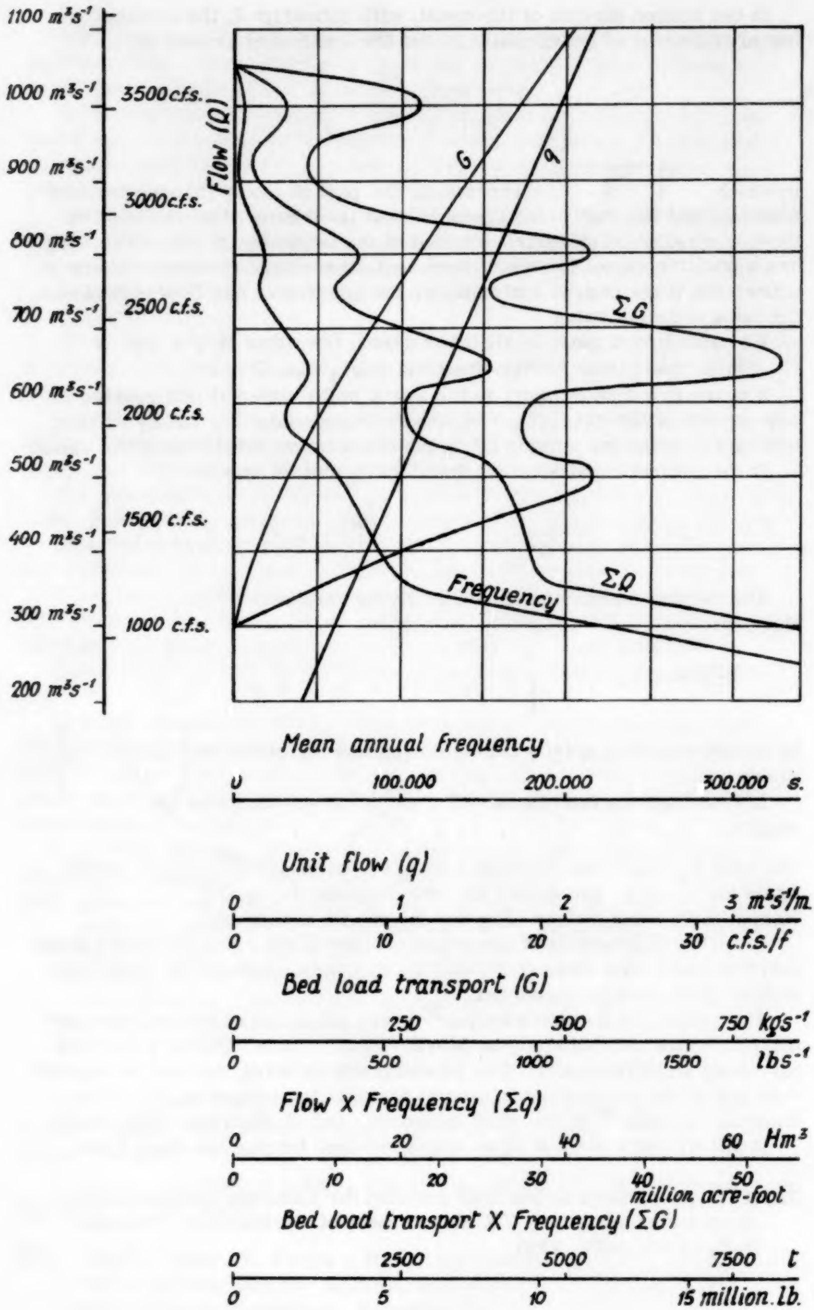
1100 m³s⁻¹
1000 m³s⁻¹
900 m³s⁻¹
800 m³s⁻¹
700 m³s⁻¹
600 m³s⁻¹
500 m³s⁻¹
400 m³s⁻¹
300 m³s⁻¹
200 m³s⁻¹
3500 c.f.s.
3000 c.f.s.
2500 c.f.s.
2000 c.f.s.
1500 c.f.s.
1000 c.f.s.
Flow (Q)
G
q
ΣG
ΣQ
Frequency
Mean annual frequency
0 100.000 200.000 300.000 s.
Unit flow (q)
0 1 2 3 m³s⁻¹/m
0 10 20 30 c.f.s./f
Bed load transport (G)
0 250 500 750 kgs⁻¹
0 500 1000 1500 lbs⁻¹
Flow X Frequency (Σq)
0 20 40 60 Hm³
0 10 20 30 40 50
million acre-foot
Bed load transport X Frequency (ΣG)
0 2500 5000 7500 t
0 5 10 15 million. lb.

Figure A

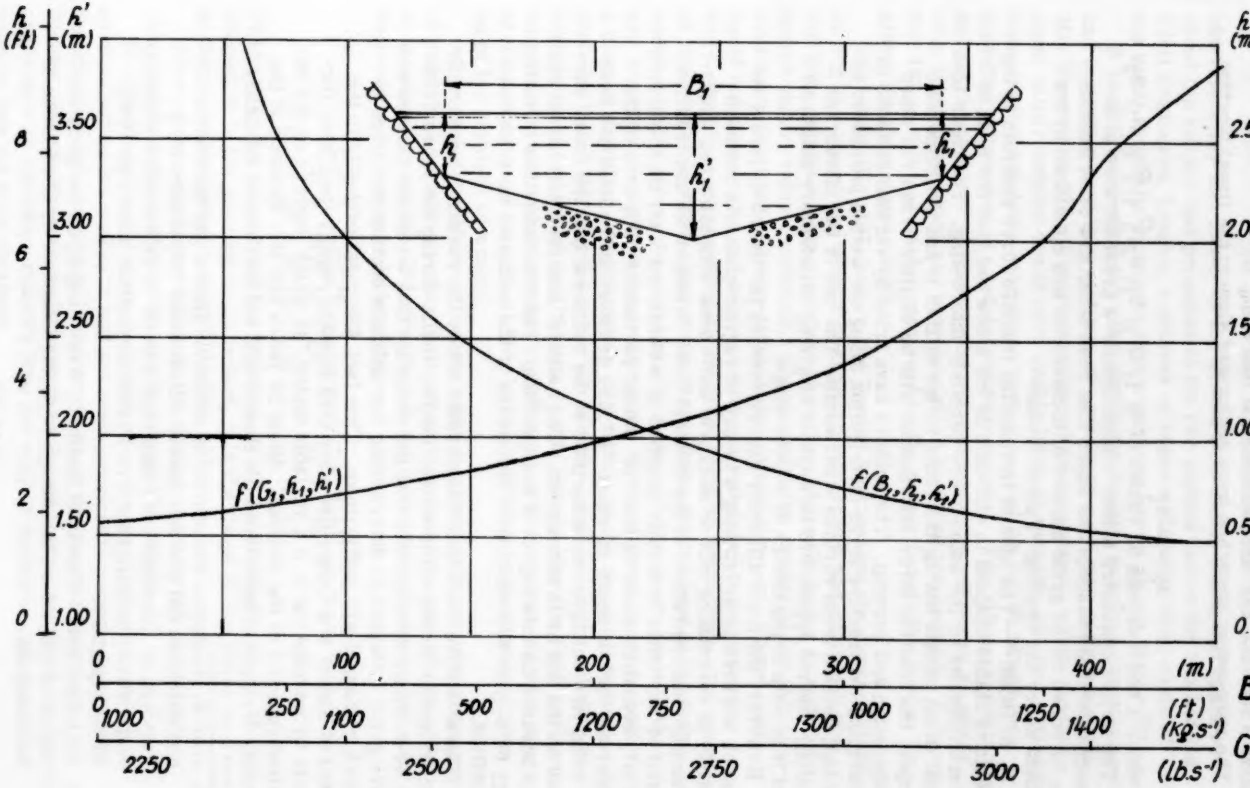

Figure B

Argentine,[29] the heavy solid material transport continuity, in the consecutive stretches was determined using the Meyer-Peter, Favre, Müller's formula, the most advanced at that time.

The successive stretches have conjugated slopes; the lineal function is:

$$i_2 = a\, i_1 - b$$

in which a and b depend on values of Q'_1, Q'_2, d_1, d_2, ρ_1, ρ_2, B_1, B_2.

The writer considers author's contribution a great advance in the design of stable channels and hopes that soon other new contributions can be added to the great amount of themes that are mentioned by the author under the heading "Future Studies".

N. K. BOSE[30]—The idea of introducing tractive force analysis in the design of stable channel in alluvium is not a new one, but the lines of attack followed by the authors are certainly interesting. The basic idea "that in all canals having the same ration of B to D and the same side slopes, the tractive force distribution will be similar" requires more elaboration and proving. The authors have tried by various methods to determine the tractive force distribution along the wetted perimeter of a canal section from various standpoints. The use of the membrane analogy method appears to be capable of giving satisfactory solutions and may help in the design at a later stage.

However, the main difficulty experienced so far by the different research workers in developing a theory of regime channels has been mainly in correlating silt or sediment movement with the other hydrodynamic characteristics of the channel flow. Whether we use tractive force or any other hydraulic constant of a canal, such as, mean velocity "Vm", hydraulic mean radius "R" wetted perimeter "P", area of the waterway "A" or depth of water "D", the greatest difficulties has been to bring in a suitable characteristic of the sediment that the canal carries on the bed or in suspension. The authors' analyses also do not show any advance on this aspect of the question. Their assumptions of taking K_{25} or K_{50} as representative diameters of the sediment have not been justified.

The extensive work that was carried out by the research workers in the Irrigation Research Institute, Punjab, India, during the years 1932-42 have shown conclusively that the sediment that a channel carries can have great influence in determining the ultimate section and slope to which a channel will settle down. This fact was most probably in the mind of Kutter and Ganguillet when they tried to modify the Chezy formula by introducing in it a variable factor "n" which depends on the so-called rugosity of the channel. About 50 years ago Mr. Kennedy of the Punjab Irrigation, introduced the idea of silt and turbulence explicitly

29. José S. Gandolfo—Estudio de la evolución fluvial que determina el endicamiento del Rio San Juan-Publicaciones Especiales No 2-Facultad de Ciencias Físicomatemáticas de la Universidad Nacional de La Plata (actualmente Eva Perón) Argentina- Enero de 1940, No 126, pag. 97.
30. Director, River Research Institute, West Bengal, on the progress report of studies on the design of Stable Channels by the Bureau of Reclamation.

into the subject and deduced his well known relationship -

$$V_o = KD^n$$

More recently Mr. Lacey of the United Provinces, India, had again revived the subject and proposed in his two papers before the Institute of Civil Engineers, London, a number of relationship involving some of the usual hydraulic constants with a quantity known as silt factor "f".

It is well known that the main difficulty that the previous investigators had in dealing with this problem of regime channel was in defining silt. Mr. Kennedy in his siltometer proposed an instrument, which, but for some minor defects would have enabled him to classify silt successfully—some of these defects have since been removed by Dr. Puri and the modified siltometer is used extensively in India. The siltometer that has solved the problem of classifying silt and made it possible to go ahead with silt investigation had been perfected by Mr. Vaidyanathan. A paper No. 167 on this siltometer was read by its author before the Punjab Engineering Congress in 1933.

In a paper (No. 192) before the Punjab Engineering Congress in 1936 on silt movement and design of channels the writer had examined the silt data obtained from a number of regime channels in the Punjab collected under stable conditions. The distribution curves of the silt samples were analysed and sub-divided into different types. These types could not however be put in absolutely cut and dried compartments. Very often they merge one into another. Just as a spectrum of a source of light runs from the ultra violet through the visible part to the infra red end, silt curves of a canal also run through the above types if they are analysed throughout the entire year. Each of these types indicates a certain condition of equilibrium of a canal, so the annual frequency distribution of these types of curves for any canal is a very reliable indication of the stage of equilibrium of that canal. Now the first problem was to determine what was the significance of these types, to what stage of the development of a canal they belong and what indication they give us of the stability of a canal.

After examining these silt curves and the hydraulic data for a number of stable channels the writer, in another note on the design of channels in alluvium, Paper No. 252, the Punjab Engineering Congress, 1942, had derived the following relationship:

$$A = 1.15\ Q^{.85} \quad \dots\ \dots \quad (1)$$
$$D = 0.39\ Q^{.29}/S^{0.37} \quad \dots\ \dots \quad (2)$$
$$S \times 10^3 = 2.09\ m^{.85}/Q^{.21} \quad \dots\ \dots \quad (3)$$

where A is the area of waterway in sq. ft., Q the discharge in cu. ft. per second, D is the average depth in feet, S is the slope of the water surface, m the mean diameter in mm of the bed sediment.

These three equations will give the design engineer all the information that he may possibly require to design his canals.

In this connection it must be stated here that in all these analyses carried out by the writer it had not been possible to take into account the effect of the quantity of bed movement on the regime equations. Though, efforts have recently been made by workers like Einstein, Shields and others to introduce quantity into the regime equations, no practical solution has yet been obtained.

E. W. LANE,[31] M. ASCE—The author has been very gratified by the valuable information and constructive suggestions furnished by the discussors of his paper. They have added materially to its value.

The information supplied by Mr. Leliavsky, MASCE, regarding Professor White's test is valuable, as these tests are the only hydraulic experiments known to the author which test the hypothesis of the relation of the angle of repose to the transportation of coarse sediments.

Mr. Leliavsky has listed four areas in which uncertainty exists regarding the reliability of assumptions used by the author in his canal design procedure and makes suggestions for further studies to clear up these uncertainties. As Mr. Leliavsky stated, the values of shear used by the author were the average values with respect to time, and not the maximums. In our present state of knowledge the latter is not known in enough detail to be used at present in a design method. The author is very much in favor or further study to clear up the question raised of the relation of the averages of the shear value to the maximum.

Mr. Leliavsky has also raised the question of secondary currents, and suggested studies along this line. The possibility of secondary currents being important is also suggested by Messrs. Nizery and Braudeau. This subject should also be added to the list of further studies mentioned by the author, since at present our knowledge of them is insufficient to enable them to be included in a design method.

That lift has its part in sediment transportation is becoming more clearly evident. Here also our present knowledge is insufficient to include it in a design method, and further information is therefore desirable, as Mr. Leliavsky suggests. The action producing lift does not always cause an upward force. In coarse, non-cohesive material, due to the tendency of flat particles to place themselves in a shingle like position, the force due to the curvature of the currents, may be downward instead of upward.[32]

As Mr. Leliavsky suggests the presence of loci of permanent local accelerations no doubt exist in some cases,[33] and may be quite important generally. The author welcomes study of this matter, and any other aspect of sediment transportation, for the future progress in the improvement of methods for the design of stable channels will be dependent on the rate at which our knowledge of the laws of sediment transportation increases.

The discussion of the late A. Nizery and G. Braudeau regarding the shape of the channel of minimum excavation and width is very valuable. This supports the use of the principles involved in this study as the basis for design of stable channels for conditions where this method applies. The author has been making further studies along these lines. It is greatly to be hoped that a complete report on the studies of Messrs.

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31. Prof., Dept. of Civ. Eng., Colorado Agri. and Mech. College, Fort Collins, Colo.
32. Some Observations on the Effect of Particle Shape on the Movement of Coarse Sediments. E. W. Lane and E. J. Carlson. Trans. American Geophysical Union, Vol. 35, No. 3, June 1954. pp. 458.
33. A New Method of Sediment Transportation. E. W. Lane. American Geophysical Union, Vol. 25, Pt. 6, p. 900, May 1954.

Nizery and Braudeau will soon be forthcoming.

The lack of agreement reported by Messra. Nizery and Braudeau of the tractive force distribution computed by the Leighly method with the observed results is interesting. This may account for some of the scatter of the results observed when this method was investigated under the author's direction, and supports the author's decision to use the results of the mathematical and membrane analogy methods in his proposed design method. The author agrees with Messrs. Nizery and Braudeau's idea that secondary currents are probably at least a partial explanation. The suggestions of Messrs. Nizery and Braudeau that the principles of stable channel design may be used to advantage in the study of regime conditions for natural streams is believed to be fully justified. For some time the author has been carrying on a study of the form of natural streams, and finds the principles derived for stable channels of great help in working out an analysis of this problem.

Professor Gandolfo's method for design, as illustrated by his discussion, shows that years ago he applied the principle which the author considers fundamental in the design of stable channels designed to carry a heavy sediment load, namely, that for such conditions it is necessary to determine the magnitude of the sediment load and design the canal to carry it. So far as the author has seen, this is the first application of this important principle to the design of an irrigation canal.

Under the author's definition of stable channel, it is not necessary that such a channel be always free from scour or deposit, as Professor Gandolfo's discussion suggests. A stable channel, under the definition, may alternately deposit and scour, provided the scour carries away the deposit before it has accumulated in objectionable quantities, and the deposit refills the scoured areas before they scour sufficiently to be objectionable.

Dr. N. K. Bose raises the question of the reliability of the assumption of the similarity of tractive force distribution in channels of similar cross section. The justification of this assumption is that in all but very small channels the Reynolds number is so great that the effect of the viscus forces is negligable. Under these conditions the velocity distribution is similar in geometrically similar sections. The geometrical similarity of velocity distribution from model size to prototype size, where the Reynolds number is sufficiently large, is commonly assumed in making prototype predictions by means of models. If it holds from model to prototype size, it should hold over a wide range of canal sizes.

Dr. Bose's remarks deal principally with the case where considerable quantities of sediment are transported by the canals. The studies presented by the author had not progressed far enough in this area to go much beyond a statement of the fundamental principles that the author believes apply to the design of stable channels under these conditions. These are that the canal must be so designed that it will transport substantially all the sediment brought into it, without producing sufficient tractive force on the banks and bed to cause scour. To determine the conditions necessary to transport the required quantity of sediment, use can be made of the formulas developed for the amount of sediment which will be transported under certain conditions. The greatest need

in this field is the measurement of the size and quantity of sediment transported in a considerable number of canals, so that the reliability of the various available formulae can be appraised, and if necessary new formulae developed.

The author has not been able to secure a copy of the paper describing the derivation of the formulae for canal design which Dr. Bose has proposed, and therefore he is unable to appraise it. However, it was based on extensive experience and probably a great deal of data. It is not unlikely that for the conditions in the canals which were used in developing it, it is under present conditions a more reliable method of design than one based on a computed quantity of sediment transportation. As the laws of sediment transportation become more fully known however, the author expects the analysis based cn the computed quantity of sediment transportation to eventually become more reliable than Dr. Bose's equations. For conditions of sediment load differing widely from those in the canals used as data in Dr. Bose's study, the author believes that his equations and any other design method which neglects the effect of sediment concentration, will not always give reliable results.

The writer is indebted to Mr. Leliavsky for informing him, in a private communication, that the solution mentioned in the author's paper for the shape of a channel in coarse, non-cohesive material, which would require a minimum excavation and width, was previously worked out by P. Forchheimer[34] as early as 1930 and perhaps earlier. Forchheimer included in his analysis not only the effect of the slope of the sides but also the influence of the longitudinal slope of the canal. It is doubtful however if this latter effect would ever be sufficient to significant.

The author has also discovered that the effect of side slopes on the movability of coarse, non-cohesive material involving the same basic idea as that presented by the author, but using velocities instead of tractive forces was published by A. Gostev[35] in 1928.

Since writing this paper, the author has been impressed by the importance as a stablizing factor of the deposits of fine material on the sides of many canals. Because of the cohesive nature of these deposits, the tractive forces which the sides can stand may be considerably greater when they are present. This may occur naturally in the aging process which takes place when the flows discharged down the canal increase, as more and more land is irrigated by the canal but, may also be furthered by scientific manipulation of the natural silts. It may be possible to accomplish this even more effectively by the applicating of bentonite. A thorough study of these possibilities is being started at the Colorado A & M College, Ft. Collins, Colorado, in conjunction with an extensive investigation of the possibilities of the prevention of seepage out of canals by staunching the bottom and sides of the canal with a bentonite slurry. For canals in fine, non-cohesive material, particularly

34. Hydraulik-Phillip Forchheimer—3rd Edition, 1930, p. 551, Copyright by B. G. Teubver in Leipzig, 1930. Translation No. 47-9. Research Center, Waterways Experiment Station, Vicksburg, Mississippi.
35. On Scouring Velocities A. Gostev. Irrigation News Bulletin (Russian) No. 1, Jan. 1928, pp. 65-69. (Translated by U. S. Bureau of Reclamation.)

where the presence of a load of sand in the incoming water necessitates a high tractive force to prevent it from depositing, this method, if it can be successfully developed, will greatly improve the form of canal which can be used.

In closing it is desirable to briefly summarize the views of the author regarding the subject covered by this paper as originally presented and as modified by his study of the subject since presentation and by the valuable discussions of the paper which were presented. The author believes that the fundamental principles of stable channels, as given in his paper, are very simple and can be readily understood by any one with an elementary knowledge of hydraulics. Defining a stable channel as one in which neither scour nor deposit in objectionable quantities occurs,[36] it follows that to obtain such a channel all that is necessary is to insure that at all points on the bed and banks of the canal the action of the water is insufficiently severe to cause objectionable scour but is sufficiently severe to prevent sediment carried by the water to depost in objectionable quantities. This statement gives the fundamental basis for the method of design proposed by the author. Corallary statements are (1) if the water entering the canal carries material quantities of sediment, in order that objectionable deposits do not occur, the inflowing sediment must be transported through the canal within a material loss of among and (2) that on the sides of a canal the force of gravity tends to move sediment particles down the sides toward the bottom, and this action assists the forces due to the motion of the flowing water in causing scour on the canal sides. He believes that the reliability of these statements are so evident that nearly everyone interested in this subject, after giving them a thorough study, will agree to them.

Since canal stability involves so largely the interaction of the water with the bed and banks of the canal, it seemed that a logical method of approach in devising a method of design for such channels would be a study in the nature of this interaction. It will be noticed that there are two phases of this interaction, a scour phase and a transportation phase. Since current knowledge of the science of hydraulics and fluid mechanics is not sufficient to completely analyze these phases, it is not now possible to devise a perfect method of design, but by using the best knowledge at present available, a method can be devised on these principles. While he does not expect changes in the fundamentals of his method of analysis, he hopes for and expects that some of the assumptions which it was necessary to make because of the state of knowledge of the science when the methods were adopted, will be improved upon when more adequate knowledge is available. However, it is believed that the assumptions made in the author's method are the best that is possible to make with our present knowledge.

The design of stable channels for irrigation projects will not wait for the development of a perfect method of analysis. For practical purposes all that is required is that the method be complete enough to enable designs to be made by its use, sufficiently simple to be readily understood,

36. The sides of the channel also must not slough down, but since a reasonable satisfactory analysis of this phase of stable channels is available, it has not been discussed in this paper.

logical enough to commend itself to the designing engineer, not require so much work as to make its application prohibitive, and be more reliable than other available methods. It is believed that for the conditions of small sediment loads, in its present state of development, the proposed methods meet these requirements, although considerable further advance can be made as better knowledge is obtained. For the condition of transporting water containing heavy sediment load, the reliability of the method is less certain, due to lack of knowledge of the reliability of formulae for the transportation of sediment, but for very heavy sediment loads they are believed to be more reliable than methods which do not contain the concentration of sediment as a factor. As knowledge of the science of sediment transportation increases, the reliability of the method in this part of the field will be increased.

Advantages of the author's method of analysis are (1) that it applies to all cases of stable channels, not only those in self bourne alluvium, (2) that it introduces no new emperical coefficients, but deals only in such well known concepts as shear values and angle of repose, (3) that it shows what information is necessary to further perfect the method, (4) that the refinements of new knowledge can be introduced without modifying other aspects of the method and (5) that recent unpublished analysis has shown that the principles developed can be used to explain the shape of cross section which many canals take as the water flows through them.

The author wishes to acknowledge the assistance of Prof. P. N. Lin in preparing this closing discussion.

DISCUSSION OF UNSTEADY FLOW IN OPEN-TYPE PIPE IRRIGATION SYSTEMS PROCEEDINGS-SEPARATE NO. 369

E. H. TAYLOR,[1] A.M. ASCE, A. F. PILLSBURY,[2] T. O. ELLIS,[3] and G. A. BEKEY.[4]—The very able discussion of the writer's paper by Mr. Glover is greatly appreciated, although the apparent attempt, here and elsewhere,[5,6] to glorify the effect of covers, and to minimize the effect of vents is a bit puzzling. Actually, those parts of the Coachella system where surging was a problem were made operable by a combination of covers and of gates through the baffles. No mention was made of the operating difficulties with covers, to-wit: (a) surge sometimes occurring at certain flows regardless of covers; (b) the blowing off of the covers from time to time; or (c) the necessity of decreasing the effectiveness of a given cover in order to obtain satisfactory delivery at that point. As for vents, model experiments would confirm that such field trials as were undertaken would not prove satisfactory. Until there are adequate field trials, the effectiveness of prototype vents must remain pure speculation.

1. Associate Prof. of Eng., Univ. of California, Los Angeles, Calif.
2. Prof. of Irrigation, Univ. of California, Los Angeles, Calif.
3. Engr. Assistant.
4. Junior Engr.
5. C. S. Hale, P. W. Terrell, R. E. Glover, and W. P. Simmons, Jr. Surge Control of the Coachella Pipe Distribution System. U.S. Bureau of Reclamation, Denver, Colo. Engineering monograph No. 17, Jan., 1954.
6. C. S. Hale, R. E. Glover, P. W. Terrell, and W. P. Simmons, Jr. Control of Surging in Concrete Pipe Distribution Systems. A.C.I. Proc. title No. 50-33, Mar., 1954.

DISCUSSION OF HUMID AREA SOILS AND MOISTURE FACTORS FOR IRRIGATION DESIGN PROCEEDINGS-SEPARATE NO. 426

GEORGE H. HARGREAVES[1], A.M. ASCE—There has long been a need for a better understanding of soil, plant, and water relationships and their use in irrigation design. The engineer designing a canal system or a sprinkler system must know the seasonal amounts of water to be delivered and the required rates of delivery for specified periods. Mr. Larson has clearly outlined the crop, soil and moisture factors necessary for proper design. In the use of these factors, however, not only is caution required because of local deviations from average conditions but also because of the limitations of some of the factors themselves.

Moisture Level and Yield—A large number of experiments show that for most crops growth is largely independent of the amount of moisture as long as there is readily available moisture in the crop root zone. Plants appear to take moisture as readily when the moisture content is only slightly above the permanent wilting point as when it is at the field capacity. Veihmeyer and Hendrickson[2] studied the effect of moisture level upon the yield and quality of crops and found no significant difference until the soil moisture in contact with the roots approached the permanent wilting point. Potatoes are known to be an outstanding exception to the above rule as well as certain other coarse rooted plants such as celery, corn and lettuce. It seems probable that although irrigation applications for some crops should be made when the soil moisture level is fairly high, for many crops this practice would lead to a waste of labor and water.

Moisture Availability from Soils—Soil texture is an important factor determining the amount of moisture readily available to the crops. There also seems to be a definite relationship between the origin and physical and chemical properties of soils and their moisture relationships (ability to hold readily available moisture). Soils mapped as sand have been known to hold as much as 1.4 inches of readily available moisture per foot of depth. Medium textured soils (loams and clay loams) hold from 0.7 to 2.7 inches per foot while some clays hold as much as 3.0 inches. Because of these wide variations average values based upon soil texture should be used with reservation.

1. Civ. Engr., Inst. of Inter-American Affairs, Port-au-Prince, Haiti.
2. Veihmeyer, F. J. and Hendrickson, A. H. "Water Holding Capacity of Soils, and its Effect on Irrigation Practices", Agricultural Engineering, Vol. 19, No. 11, 1938 and "Irrigation Experiments with Grapes", Calif. Agr. Exp. Station, Bull. 728, 1950.

TABLE XI

MONTHLY AND SEASONAL CONSUMPTIVE-USE COEFFICIENTS

Davis, California [a]

CROP	MONTHLY CONSUMPTIVE USE COEFFICIENTS "k"									SEASONAL COEFF. "K"
	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	
Alfalfa	0.37	0.73	0.81	0.90	1.04	0.93	0.84	0.41	0.33	0.76
Asparagus	0.15	0.11	0.15	0.23	0.65	1.12	1.11	1.01	0.41	0.57
Beans				0.21	0.39	0.91	0.67			0.54
Cantaloupes			0.30	0.41	0.52	0.84	0.51			0.52
Carrots	0.15	0.19	0.24	0.69	0.91	0.39				0.49
Celery				0.21	0.19	0.35	0.60	0.71	0.69	0.41
Corn				0.17	0.54	0.58	0.34	0.10		0.37
Fruit (Deciduous)	0.12	0.47	0.61	0.99	1.00	0.76	0.57	0.37		0.67
Grain & Hay	0.44	0.79	0.73	0.17						0.52
Grapes (Muscat)		0.13	0.30	0.35	0.44	0.37	0.34	0.16		0.31
Ladino Clover	0.44	0.85	0.91	1.03	1.17	1.05	0.93	0.45		0.90
Onions (early)	0.24	0.47	0.38							0.38
Onions (late)	0.24	0.47	0.38	0.41	0.39					0.39
Peas	0.24	0.38	0.61	0.41						0.43
Potatoes (early)	0.49	0.75	0.92	0.83						0.77
Tomatoes				0.44	0.58	0.98	0.88	0.83		0.73

a) Based on consumptive use data published in "Suggested Subject Matter for Presentation at Irrigation Meetings" by L. J. Booher, 1948, Col. of Agr., Ext. Serv., Davis, California. File 12.1.

Consumptive Use Coefficients—Experiment stations need to make many more measurements of consumptive use. Due to the present lack of measurements it is frequently necessary to apply data collected in one area to another. In order to do this successfully considerable knowledge of the factors which influence consumptive-use is necessary. Consumptive-use for a specific crop varies with the rate and stage of growth of the plant and its leaf surface area as well as with the climatic factors of temperature, relative humidity, wind and daylight hours. Because all of these factors vary considerably throughout the growing season, irrigation design should be based upon monthly or short period values of consumptive-use rather than upon seasonal consumptive use coefficients.

In the computation of monthly rates of consumptive-use at a given location based upon known data from another area several methods may be employed. Where U. S. Weather Bureau pan evaporation is available at both locations a comparison of evaporation rates forms a good index of relative consumptive-use rates. Where evaporation data are not available either the Lowery-Johnson[3] or the Blaney-Criddle methods may be used. The Lowery-Johnson method offers some advantages where differences in relative humidity are of importance. Maximum daily temperatures (employed in the Lowery-Johnson method) and consumptive use both increase as relative humidity decreases. The Blaney-Criddle method offers the advantages of ease of computation and availability of data. Unfortunately monthly consumptive-use coefficients are available for only a few crops and in only a few locations.

The use of seasonal consumptive-use coefficients, given by Mr. Larson in Table IV, does not necessarily result in consumptive-use values that correlate closely with monthly or peak consumptive-use requirements to be used in irrigation design. Table XI gives monthly and seasonal consumptive-use coefficients computed for Davis, California by using the Blaney-Criddle method. Consumptive-use coefficients for months of maximum growth and leaf surface area average 48 per cent higher than seasonal coefficients. This difference, although of considerable importance, is reduced in humid areas.

HARRY F. BLANEY[4,5], M. ASCE—This paper provides a long needed stimulus for additional research in irrigation requirements in humid areas. This is a matter of importance not only in eastern United States but in areas throughout the world where irrigated agricultural development is being expanded. Mr. Larson mentions the Blaney-Criddle method of determining consumptive use of water from climatological data in the text and in tables III, IV, and V, but leaves the reader in doubt as to the procedure. (1)

Briefly, the procedure is to correlate existing consumptive-use data with monthly temperature, percentage of daytime hours, precipitation, frost-free (growing) period, or irrigation season. The coefficients so

3. ASCE Transactions, Vol. 107, 1942, Page 1243.
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developed for different crops are used to translocate or transpose consumptive-use data from one section to other areas in which climatological data alone are available. Research studies indicate that consumptive use varies with the temperature and the extent of daytime hours, and with the available moisture (precipitation, irrigation, and ground water). By multiplying the mean monthly temperature (t) by the monthly percentage of daytime hours of the year (p), a monthly consumptive-use factor (f) is obtained. Then it is assumed that the consumptive use varies directly as this factor when an ample water supply is available. Expressed mathematically, $U = KF = \Sigma\ kf$, in which U is the consumptive use of crop in inches for any period; F is the sum of the monthly consumptive-use factors for the period (sum of the products of mean monthly temperature and monthly percentage of daytime hours of the year); K is the empirical consumptive-use coefficient (irrigation season or growing period); and the other terms are as previously defined.

In table IV Mr. Larson shows tentative seasonal coefficients "K" for formula (U = KF = Consumptive Use in inches). In 1950 the writer inspected the irrigated areas along the Atlantic Coast from Florida to Massachusetts, and suggested tentative values of "K" in connection with the design of sprinkler irrigation systems. These coefficients are in agreement in most instances with those shown in table IV.

An analysis of the available data in the South Atlantic area indicates that the consumptive-use coefficients should be greater in the inland areas than along the coast. Table 1 shows the tentative coefficients proposed by the writer for the South Atlantic area. Additional research studies are needed to develop monthly coefficients (k) for various crops grown in the Southern states. Table 2 illustrates the method of computing the monthly consumptive use and irrigation requirements when data are available.

LITERATURE CITED

(1) "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data", by Harry F. Blaney and Wayne D. Criddle, Div. of Irrig. and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture, SCS-TP-96, Washington, D. C., 1950.

Table 1. Tentative seasonal coefficients K for use in the consumptive-use formula U = KF, in the South Atlantic area of the United States.

Crop	Period	Area	
		Coastal (K)	Inland (K)
Alfalfa	Winter	0.60	0.60
	Frost-free	.70	.80
Corn	" "	.60	.70
Cotton	" "	.60	.65
Deciduous (Orchard)	" "	.55	.65
Grapefruit	Annual	.55	
Grain (small)	Winter	.50	.50
	Frost-free	.60	.65
Grass pasture	Winter	.60	.60
	Summer	.70	.80
Potatoes	Frost-free	.60	.65
Rice	" "	.85	1.00
Strawberries	Winter	.50	.50
	Frost-free	.55	.60
Tomatoes	" "	.60	.65
Vegetables	" "	.50	.55
Watermelons	" "	.55	.60

Table 2. Computed monthly consumptive use and irrigation requirement for grass pasture, Charleston, S. C., for dry year 1925.

Month	Mean monthly temper-ature (t)	Monthly percent of daytime hours (p)	Monthly consumptive-use factor 1/ (f)	Monthly consumptive-use coefficient (k)	Monthly precipi-tation (r)	Monthly consump-tive use 2/ (u)	Consump-tive use minus rainfall (u-r)	Irriga-tion require-ment 3/ (i)
	°F.	Percent			Inches	Inches	Inches	Inches
Mar.	59.2	8.36	4.95	0.60	1.28	2.97	1.69	2.4
Apr.	66.8	8.77	5.86	.60	1.89	3.51	1.62	2.3
May	71.0	9.67	6.86	.65	1.96	4.46	2.50	3.6
June	79.8	9.63	7.68	.65	5.49	4.99	—	—
July	82.8	9.83	8.14	.70	2.38	5.70	3.32	4.7
Aug.	81.2	9.31	7.56	.70	1.62	5.29	3.67	5.2
Sept.	77.0	8.34	6.42	.65	1.94	4.17	2.23	3.2
Oct.	68.8	7.91	5.44	.60	3.08	3.26	0.18	—
Season 3/1 - 10/1					Total	34.35		21.4

1/ $f = \frac{t \times p}{100}$

2/ $u = kf$

3/ Based on field-irrigation efficiency of 70 percent.